Combined Single Axis Attitude Control and Energy Storage Demonstration and NASA GRC

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Barbara Kenny – NASA GRC

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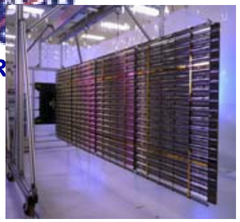
Outline of Presentation

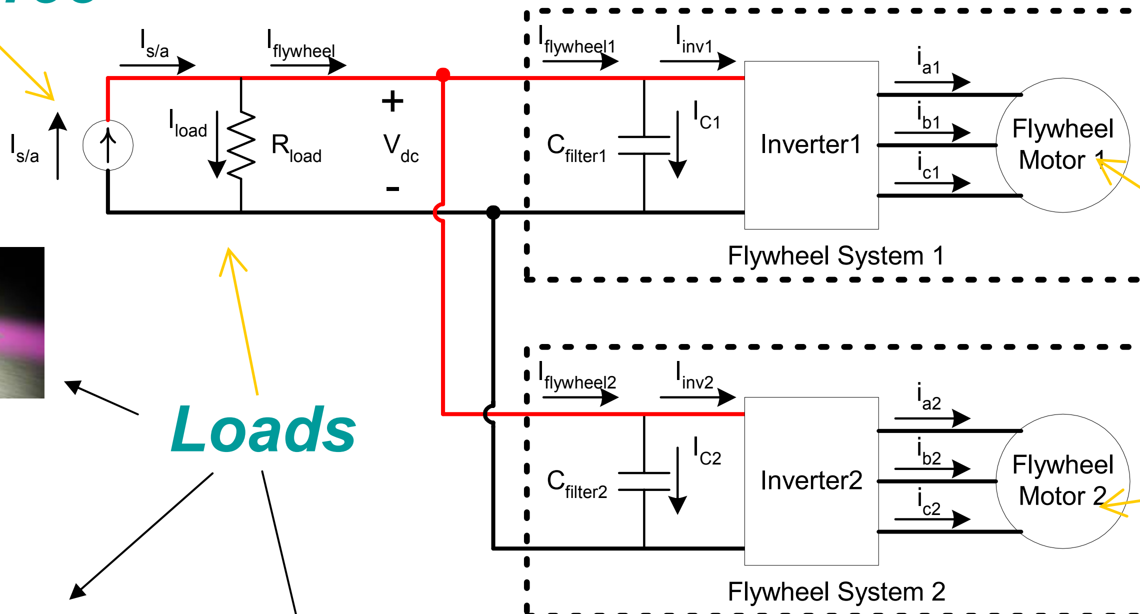
- GRC in-house flywheel technology development and facilities (Ralph Jansen)
- Single axis and energy storage control (Peter Kascak)
  - Derivation of theory
  - Simulation results
  - Experimental results
- Future Work (Ralph Jansen)



Source

PMAD1

Inverter and Controls1



Loads

PMAD2

Inverter and Controls2

GRC Flywheel Hardware Buildup

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2000

4/00 Dev 1 Delivered from USFS

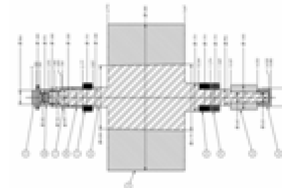
5/00 Low Energy Flywheel Facility at GRC

6/00 Dev 1 Mag Bearing And Motor Electronics Compete

8/00 Dev 1 to 20K RPM at GRC

2001

2/01 HSS Delivered from USFS



11/01 D1 CDR Review New Rotor, T/D Bearings Motor/Gen Sensors

2002

3/02 HSS Rebuilt Sens/TD

Dever-Sensors IECEC2001

5/02 HSS to 58KRPM

Dever-MB Control IECEC2002

7/02 HEFF Containment Complete

Trase- H2O Cont IECEC2002

Jansen- D1 Design IECEC2002

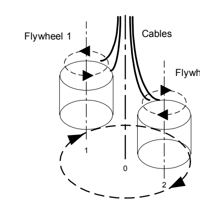
10/02 D1 Assembled, levitated, and spun

2003

Dever-MB Control Lebron-MB Filters Jansen-MB PWM's IECEC2003

2/03 D1 & HSS Operating In HEFF

7/03 Single Axis IPACS Experimentally Demonstrated



8/2003

http:space-power.grc.nasa.gov/ppo/flywheel/fly.html

GRC Motor Control Algorithm Development

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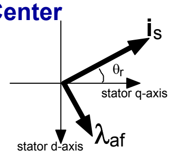
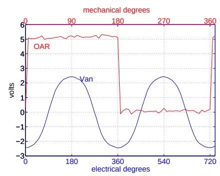
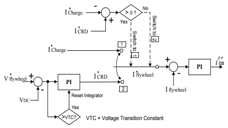
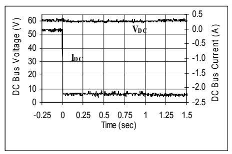


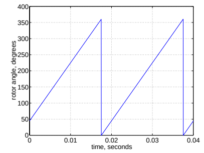


6/00
M/G Speed
Control for
Dev 1

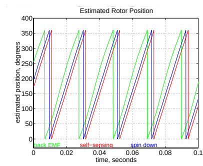




5/01
Bus Regulation
with 1 Flywheel

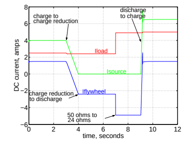


10/01
HSS Low
Speed
Sensorless
Control



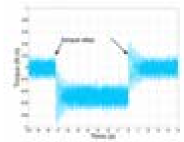
5/02
HSS High
Speed
Sensorless
Control

Kenny-Sensorless Bus
IEMDC 2003

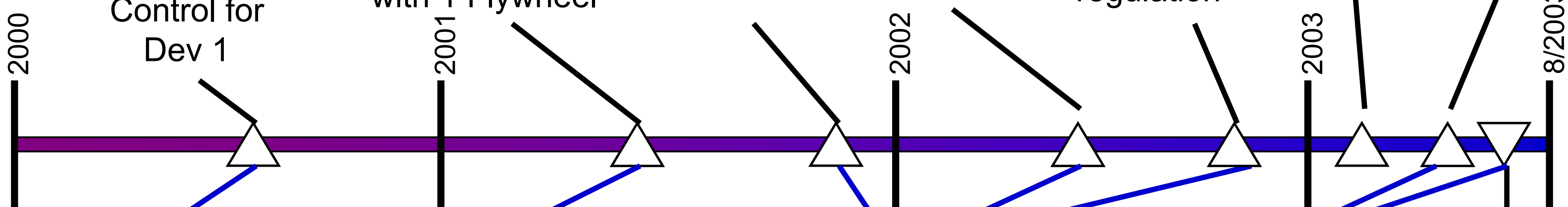


12/02
D1
Sensorless
bus
regulation

2/03
D1 & HSS
operated in
parallel
in speed
mode



4/08
2 FW Bus
regulation
& torque



Features:
1) Rotating ref frame current regulator
2) Stationary frame current regulator

Kenny-MG Control
IECEC2001

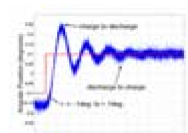
Features:
1) Charge current regulation
2) Discharge bus voltage regulation

Kascak-Bus Regulation
IECEC2001

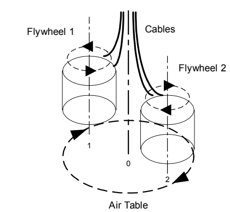
Features:
1) Signal injection method for low speed
2) Back EMF method for high speed

Kenny-Sensorless
IECEC2002

Features:
1) 2FW sensorless
2) Bus regulation
3) Attitude control



7/03 Single Axis IPACS Experimentally Demonstrated



Kascak-Simulation
IECEC2002
Kenny-Torque-Submitted
Kascak-Attitude-Submitted

http:space-power.grc.nasa.gov/ppo/flywheel/fly.html

Flywheel Modules

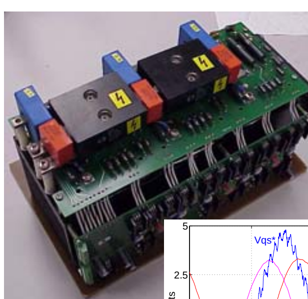
- D1 Flywheel Module
  - Rotor
    - 330 Whr - Toray 4 ring rim
    - Monolithic steel hub
  - Motor/Generator
    - 1kW, 80V l-l, 2 pole Ashman Technology
  - Magnetic Bearing
    - 4 pole homopolar radial
    - 4 pole hompolar/2 axial pole combo
    - Eddy current sensors
  - Touchdown Bearing
    - Combo/radial design allows axial growth
  - Housing
    - Vacuum

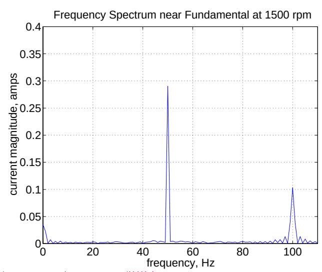
- High Speed Shaft
  - Rotor
    - 17 Whr – no rim
    - Monolithic steel hub
  - Motor/Generator
    - 3kW, 220V l-l, 4 pole Ashman Technology
  - Magnetic Bearing
    - 4 pole homopolar radial
    - 4 pole hompolar/2 axial pole combo
    - Eddy current sensors
  - Touchdown Bearing
    - Redesigned for higher load
  - Housing
    - Vacuum

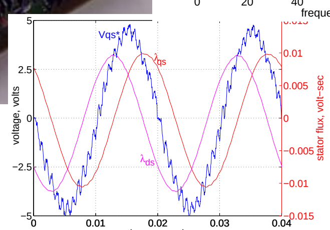
Power and Control Electronics

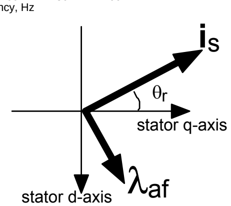
- Motor / Generator Power
  - Six switch FET inverter – APT
  - 65 kHz switching frequency
  - GRC PWM board
  - DC bus filter
  - AC output filter
- Motor / Generator Control
  - dSpace control hardware
  - GRC algorithms
  - Current feedback

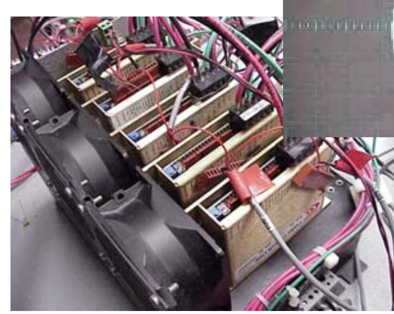
- Magnetic Bearing Power
  - 2 state PWM bridge
  - 30 kHz switching frequency
  - DC bus filter
  - AC output filter
- Magnetic Bearing Control
  - dSpace control hardware
  - GRC algorithms
  - Eddy current position sensor feedback

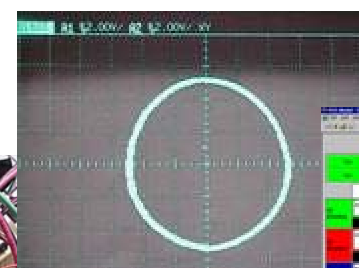


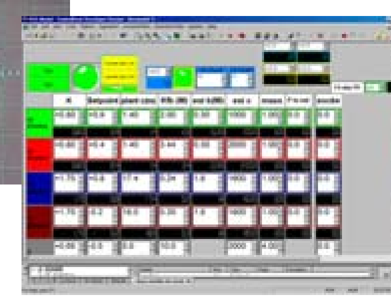








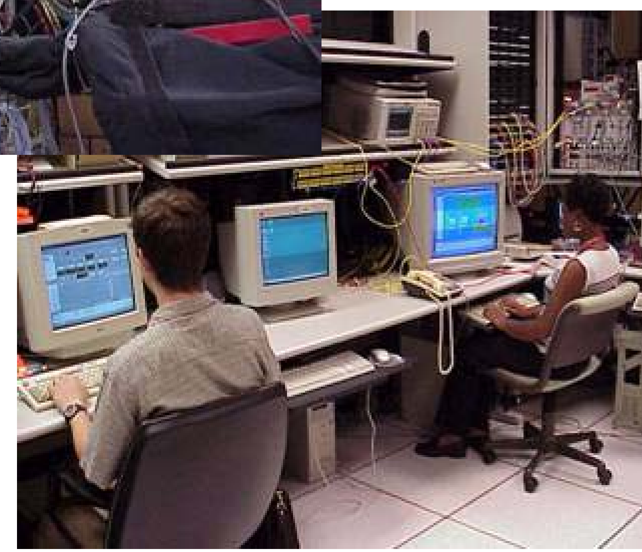




Dual Flywheel Test Facility (HEFF)

Electronics

Flywheel modules

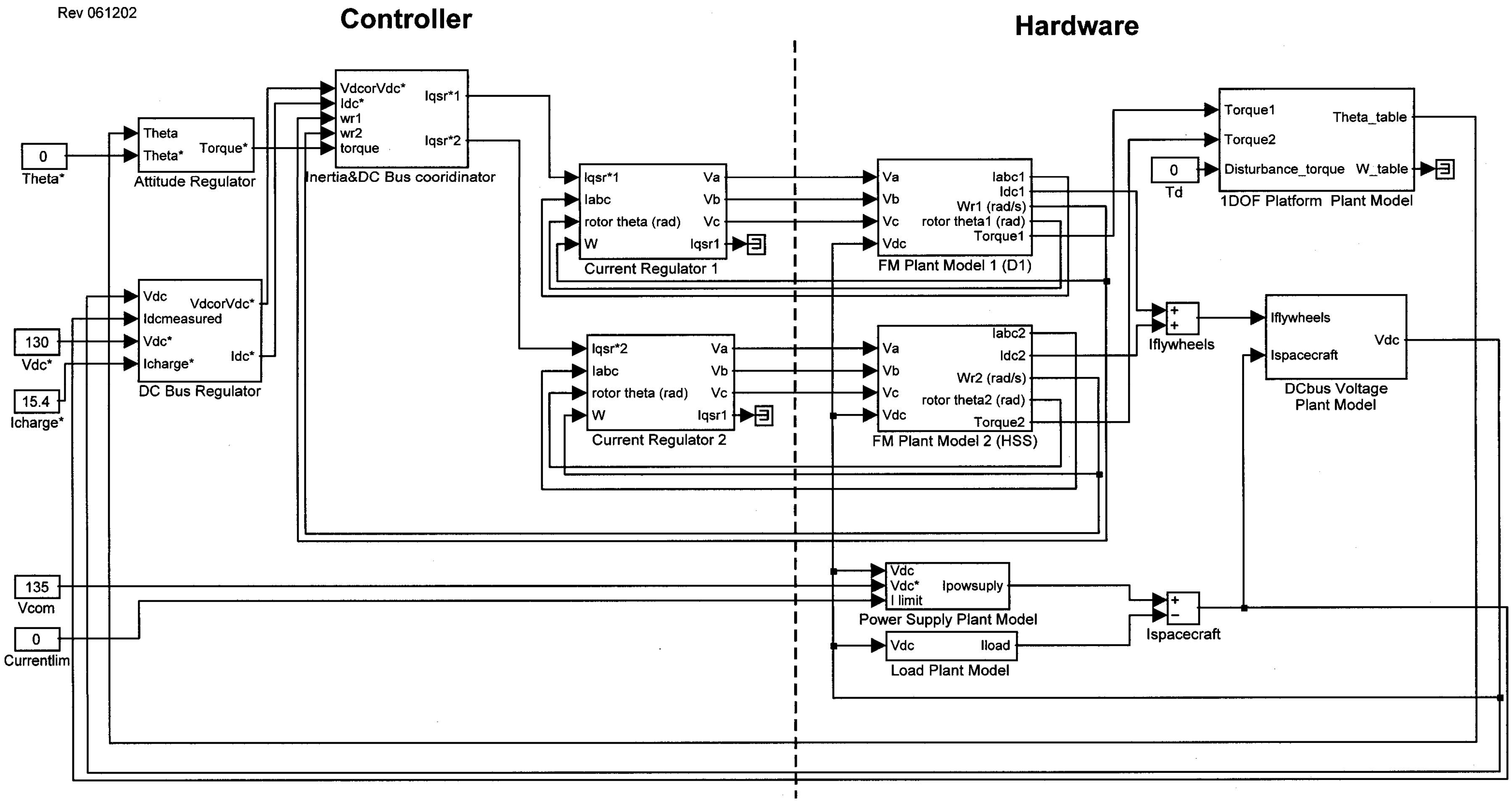


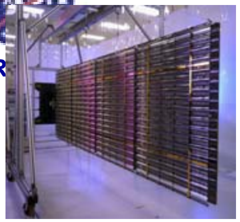
Control Room

Single Axis Attitude Control and Energy Storage Demonstration

- Theoretical derivations
  - Electrical (power and DC bus regulation)
  - Mechanical (attitude control)
- Experimental results
  - Open loop torque control
  - Closed loop position control

Control Configuration

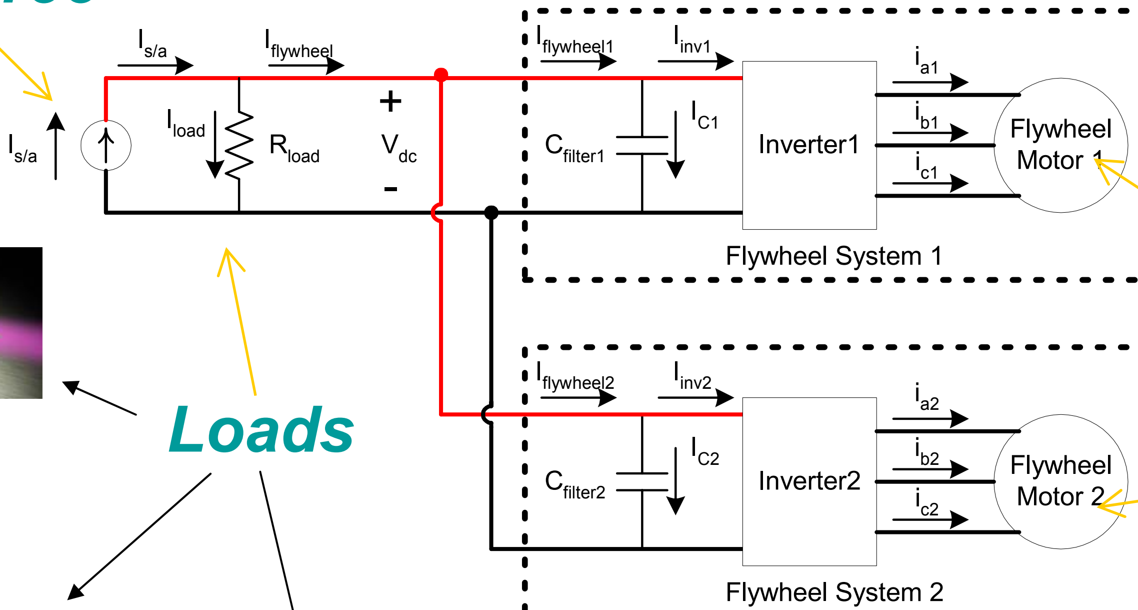




Source

PMAD1

Inverter and Controls1



Loads

PMAD2

Inverter and Controls2

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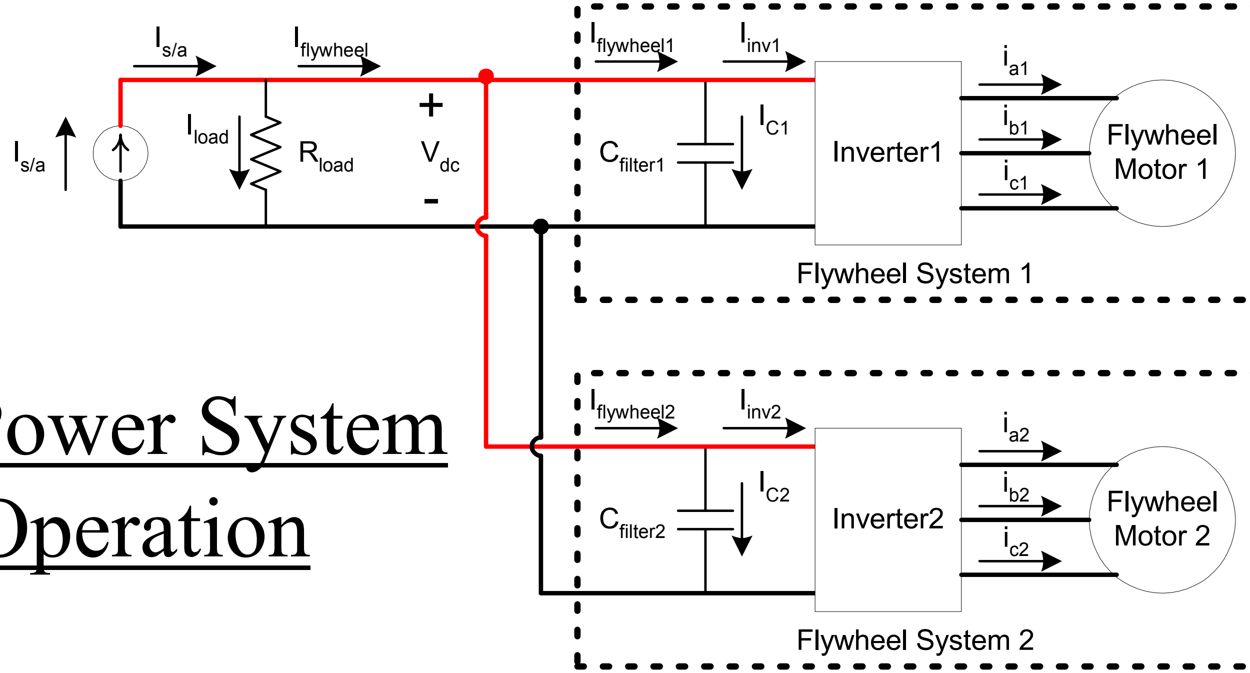

Required Power System Modes of Operation

Mode	Current	DC Bus Voltage
Full Sun "Charge"	$I_{s/a} = I_{load} + I^*_{charge}$ $I_{flywheel} = I^*_{charge}$	Regulated by solar array system
Partial Sun "Charge Reduction"	$I_{load} + I^*_{charge} > I_{s/a} > 0$ $I^*_{charge} > I_{flywheel}$	Regulated by flywheel system
Eclipse "Discharge"	$I_{load} = - I_{flywheel}$ $I_{flywheel} < 0$	Regulated by flywheel system

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Power System Control

- Achieved through control of motor currents
- Based on power balance
  - Steady state assumption
  - Neglects inverter losses
  - AC power ≈ DC power

$$I_{flywheel,m} \approx \frac{3\omega_{r,m}\lambda_{af,m}}{2V_{DC}} i^{r}_{qs,m}$$

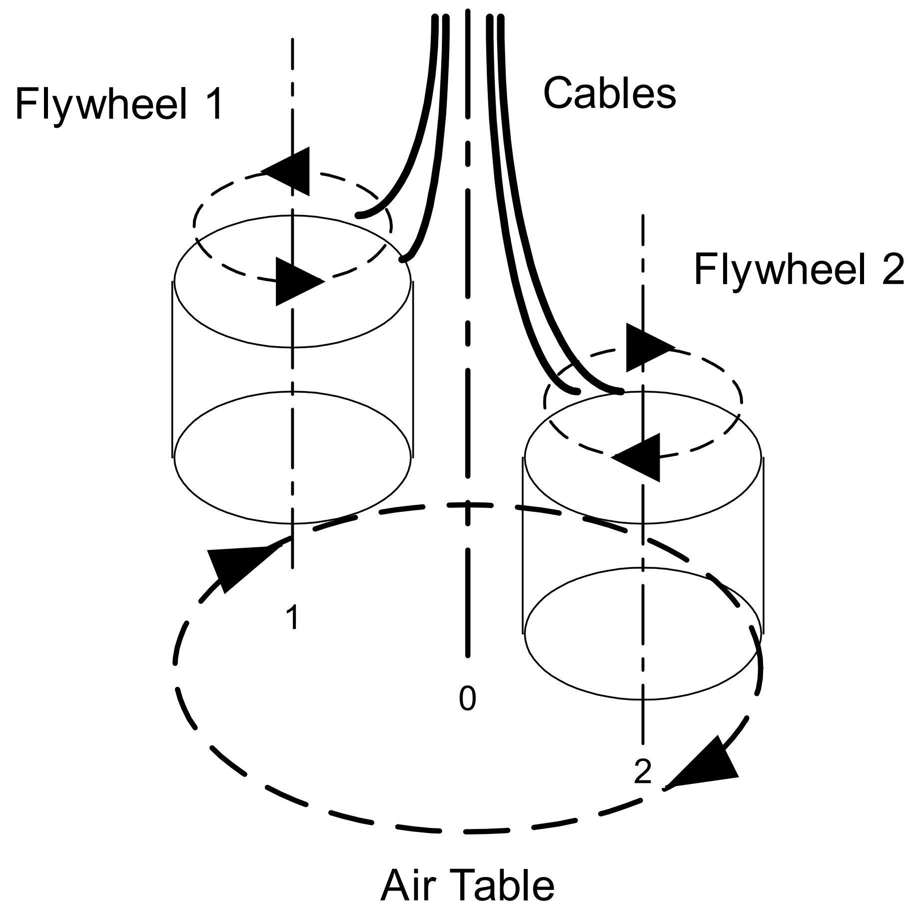
- $I_{flywheel,\ m}$ is the DC side current associated with the mth flywheel.
- $\omega_{r,m}$ is the mth flywheel speed.
- $\lambda_{af,\ m}$ is the back emf constant of the mth flywheel.
- V_{dc} is the DC bus voltage.
- $i^{r}_{qs,m}$ is the motor control current for the mth flywheel.

Motor Torque Control

- Also achieved through control of motor current.
- Based on field orientation
  - Motor torque is proportional to motor control current:

$$T_{e,m} = \frac{3}{2}\frac{P}{2}\lambda_{af} i_{qs,m}^{r}$$

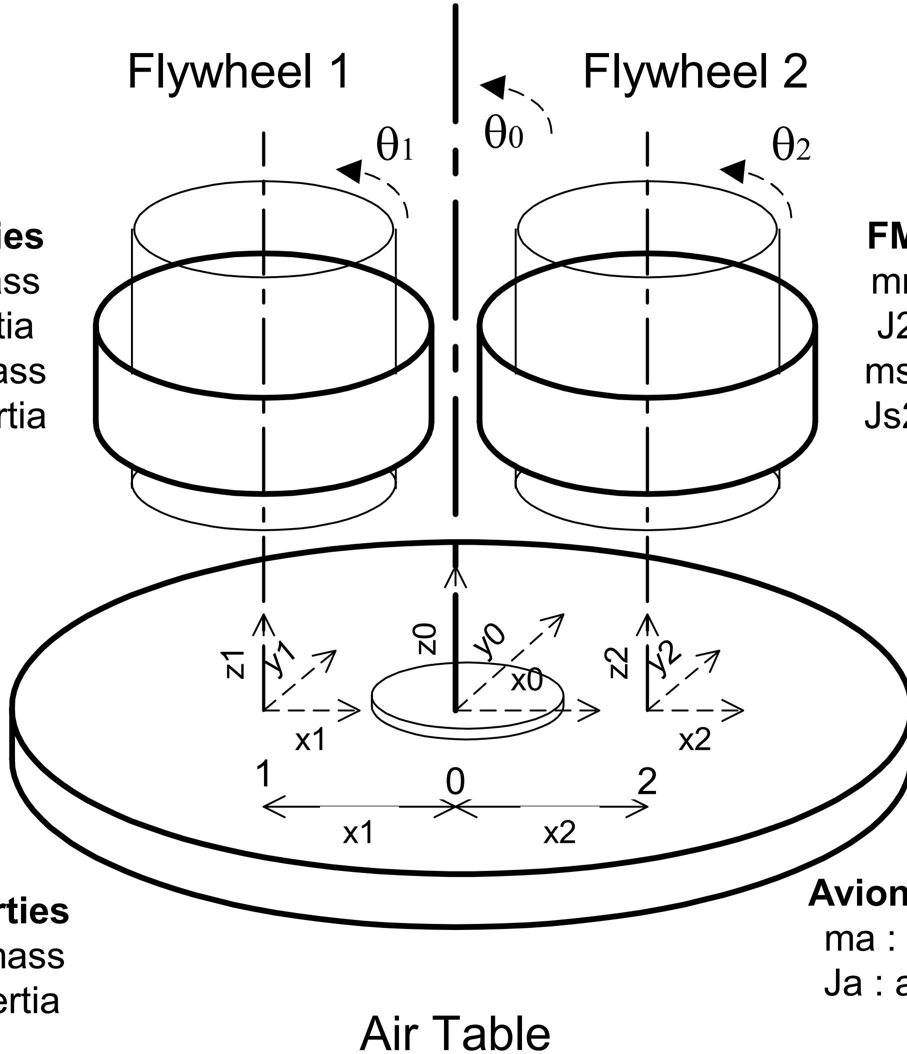
Mechanical Schematic



Free Body Diagram

FM 1 Properties
mr1 : rotor mass
J1 : rotor inertia
ms1: stator mass
Js1: stator inertia

FM 2 Properties
mr2 : rotor mass
J2 : rotor inertia
ms2: stator mass
Js2: stator inertia



Base Properties
mb : plate mass
Jb : plate inertia

Avionics Properties
ma : avionics mass
Ja : avionics inertia

Equations of Motion

$$J\ddot{\theta}_0 + c\dot{\theta}_0 + k\theta_0 = \sum T$$

$$\sum T = T_p = -T_{m1} - T_{m2}$$

Torque and Power Coordination

- $$T_p = -T_{m1} - T_{m2} = -a i_{qs1}^r - b i_{qs2}^r$$

$$a = \frac{3}{2}\frac{P_1}{2}\lambda_{af1} \qquad b = \frac{3}{2}\frac{P_2}{2}\lambda_{af2}$$

- $$I_{flywheel} = I_{flywheel,1} + I_{flywheel,2} = c i_{qs1}^r + d i_{qs2}^r$$

$$c = \frac{3\omega_{r1}\lambda_{af1}}{2V_{DC}} \qquad d = \frac{3\omega_{r2}\lambda_{af2}}{2V_{DC}}$$

Control Solution

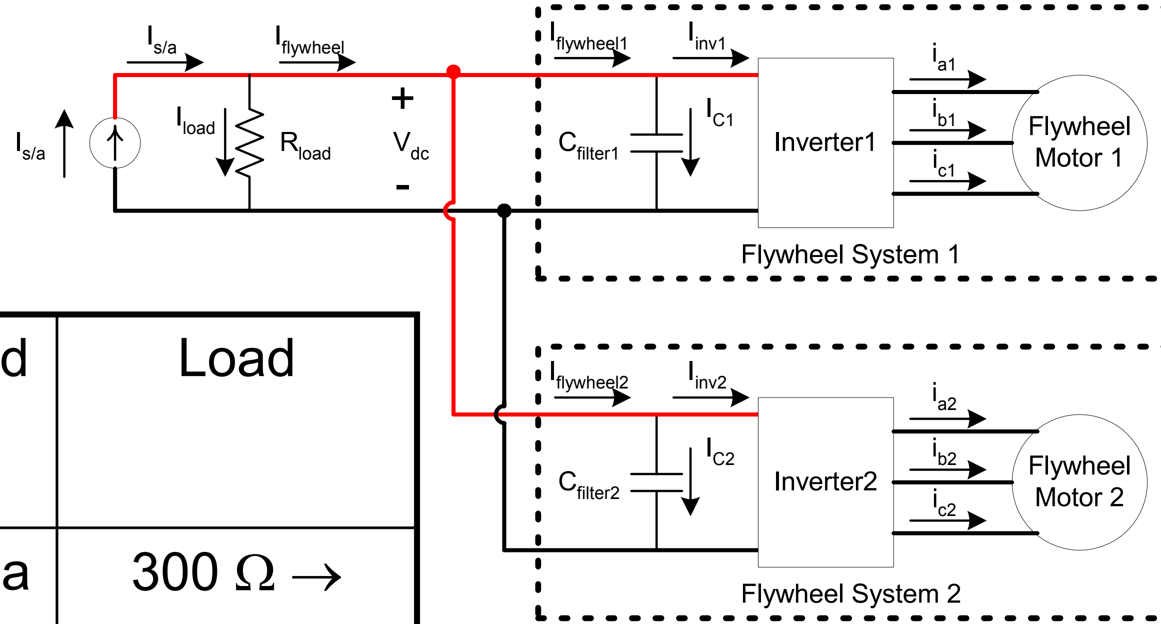
- Motor 1 control current: $$i_{qs1}^{r} = \frac{bI_{flywheel} + dT_p}{cb - da}$$

- Motor 2 control current: $$i_{qs2}^{r} = \frac{T_p + ai_{qs1}^{r}}{-b}$$

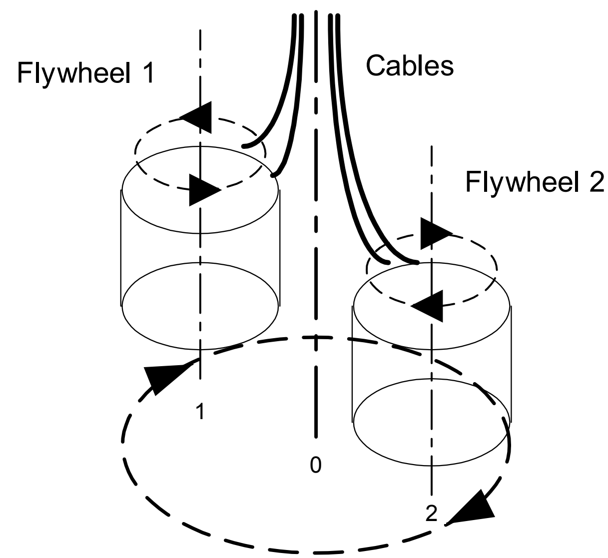
- T_p is the desired table torque
  - Either determined from a closed loop position controller or commanded in open loop fashion
- $I_{flywheel}$ is the commanded charging current in charge mode and the load current during discharge mode.

Experimental Results

- Open loop torque control



Power Regulation Mode	Commanded Values	Load
Test 1: Charge → Discharge	$I^{*}_{charge} = 1.7$ a $V^{*}_{dc} = 120$v $T^{*}_{p} = 0$	$300\ \Omega \rightarrow 120\ \Omega$
Test2: Charge	$I^{*}_{charge} = 1.7$ a $T^{*}_{p} = 0 \rightarrow -0.5 \rightarrow 0$	$300\ \Omega$
Test 3: Discharge	$V^{*}_{dc} = 120$v $T^{*}_{p} = 0 \rightarrow +0.5 \rightarrow 0$	$300\ \Omega$



Air Table

Test 1: Charge to discharge mode with a constant torque command

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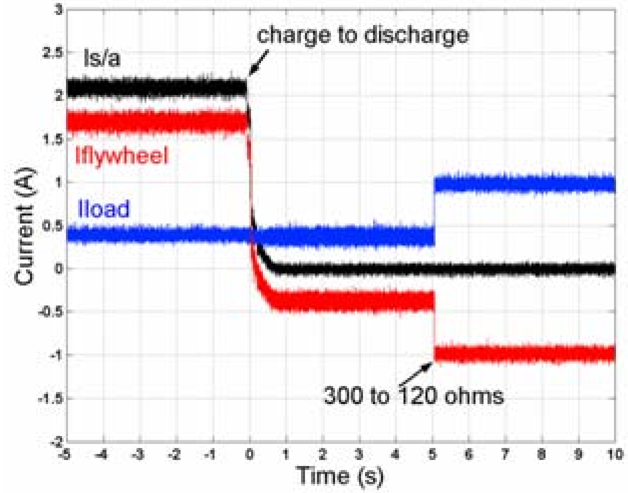
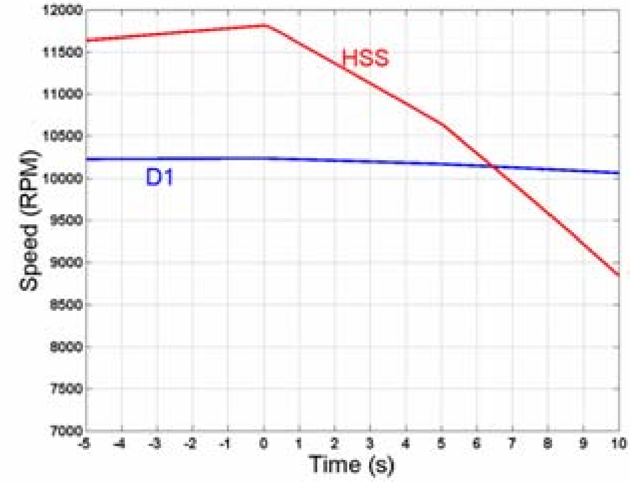
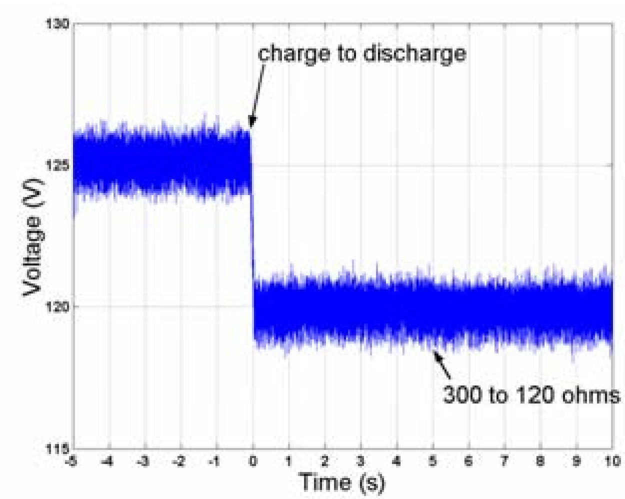


DC Currents



Flywheel speeds



DC bus voltage

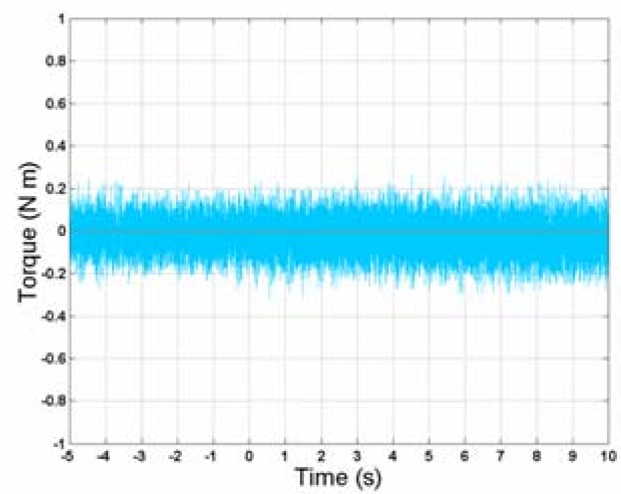


Table torque

Test 2: Charge mode with a step change in torque command

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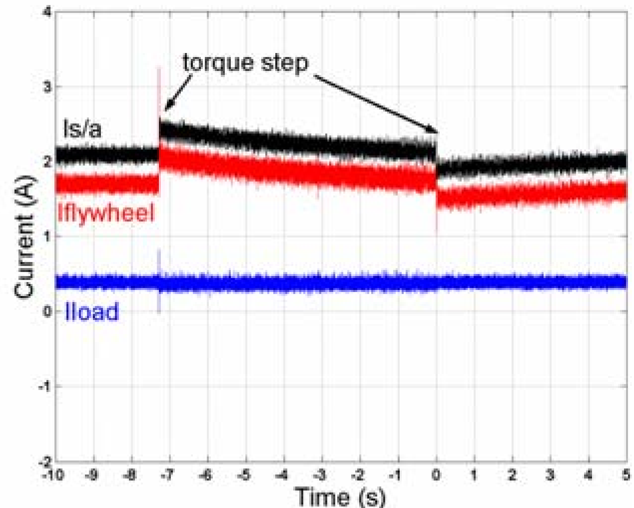
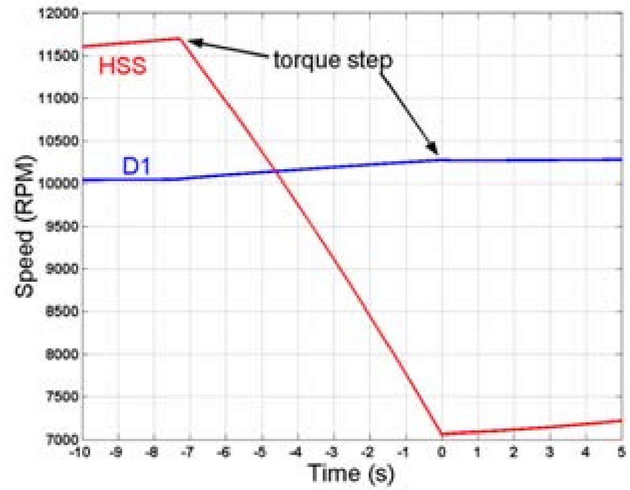
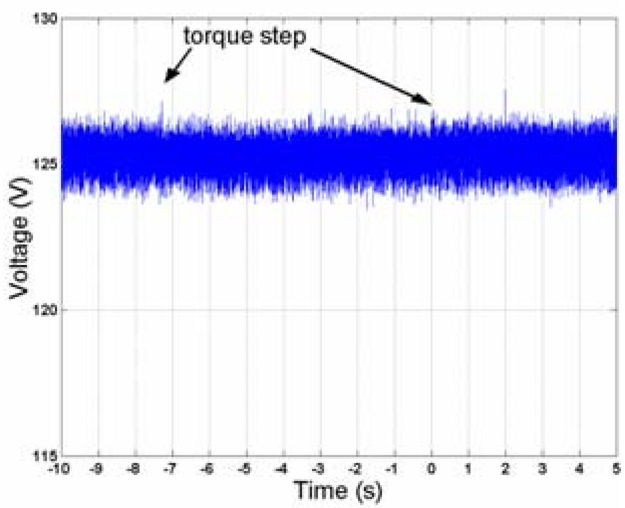


DC Currents



Flywheel speeds



DC bus voltage

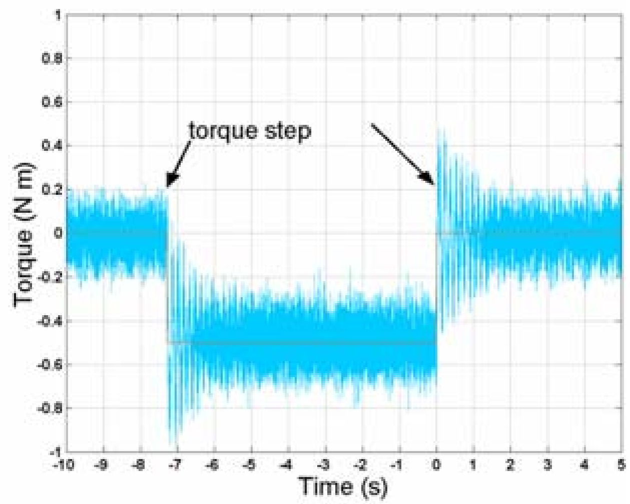
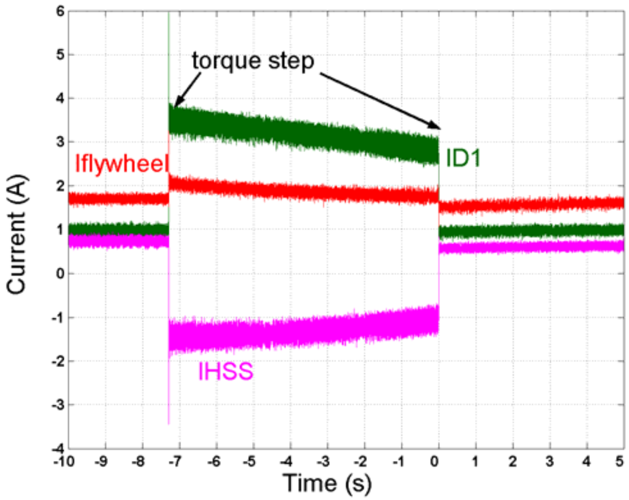
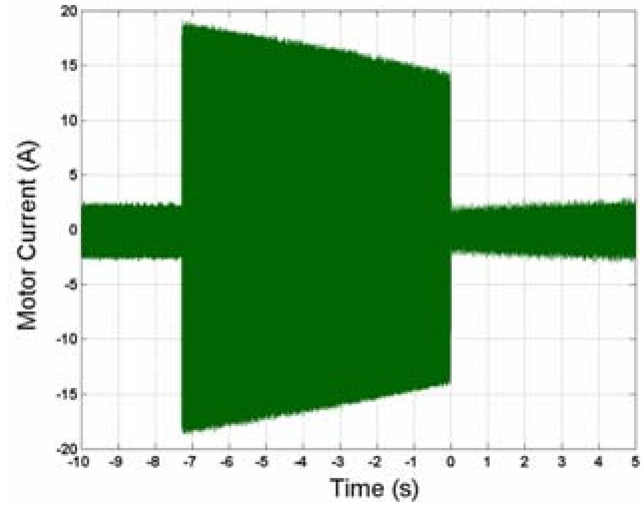


Table torque

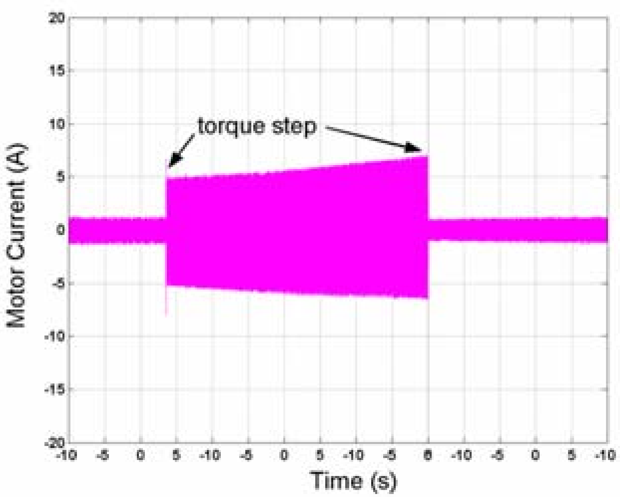
D1 and HSS currents for Test 2



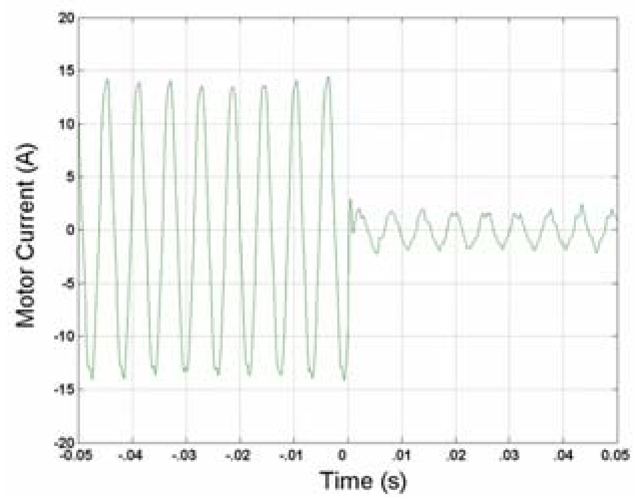
DC currents



D1 motor current

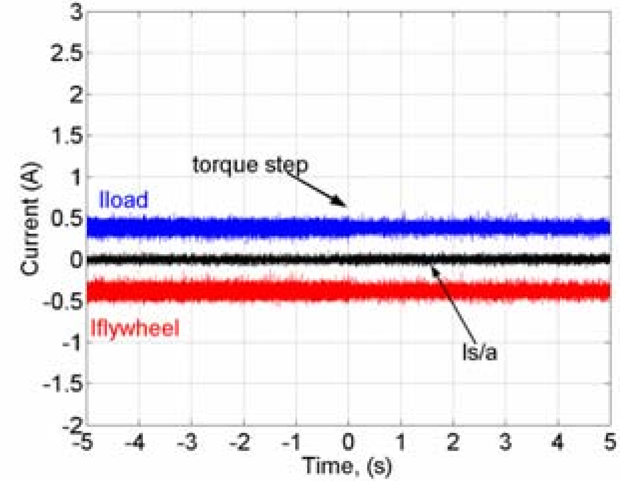


HSS motor current

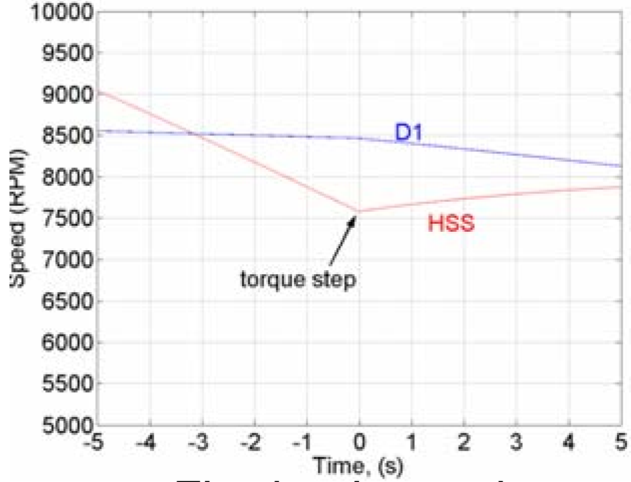


D1 motor current close-up

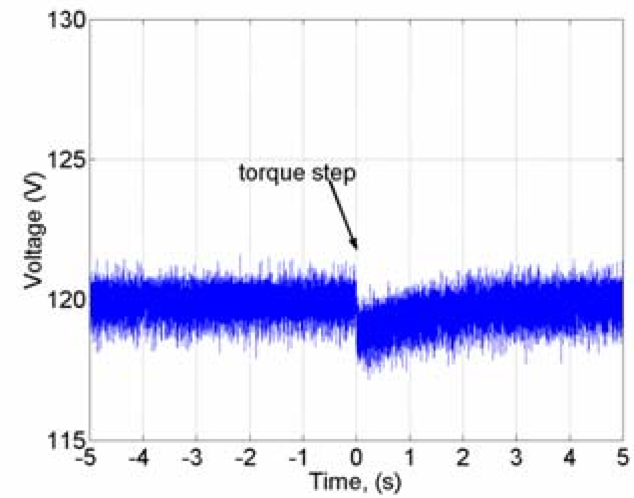
Test 3: Discharge mode with a step change in torque command



DC Currents



Flywheel speeds



DC bus voltage

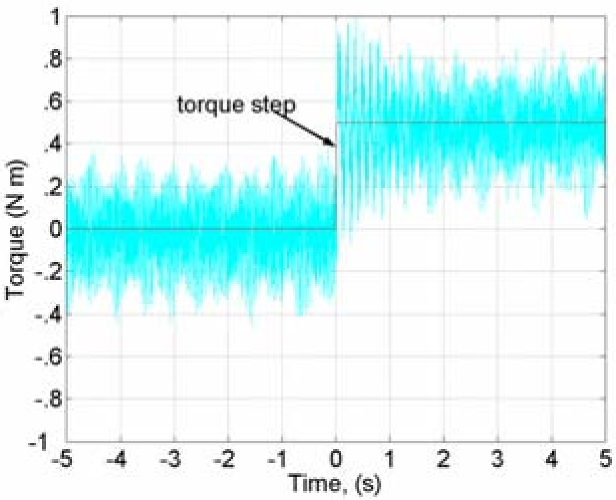
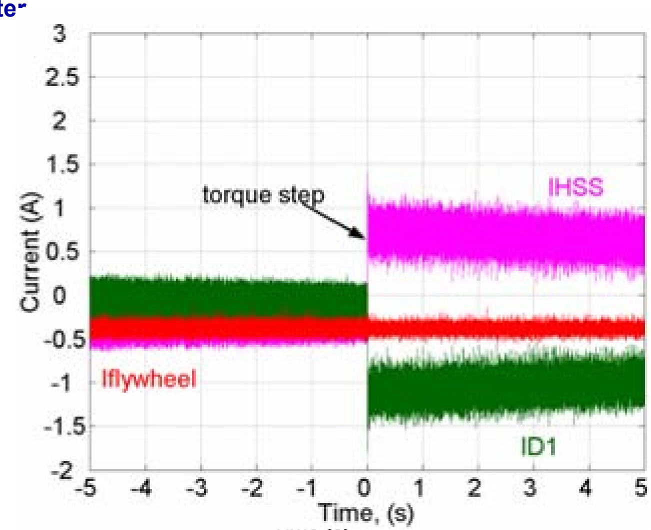
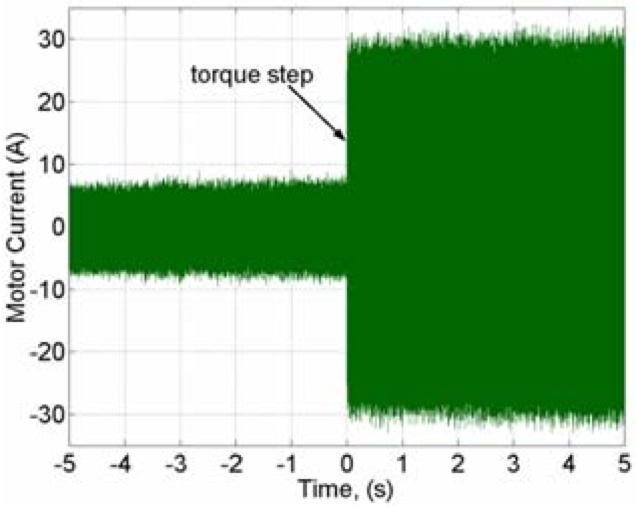


Table torque

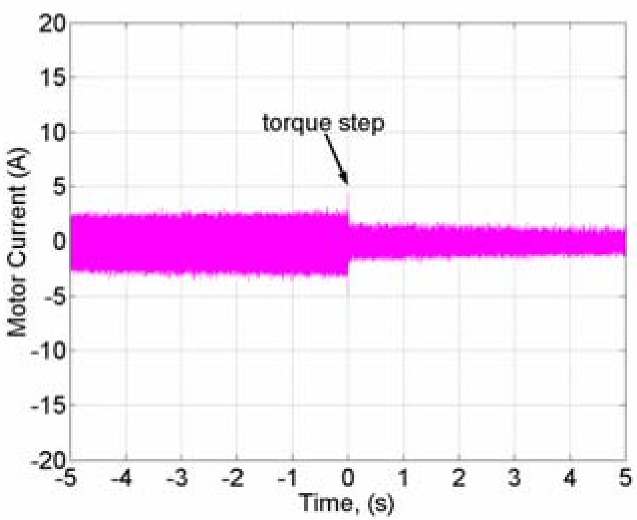
Additional Test 3 results



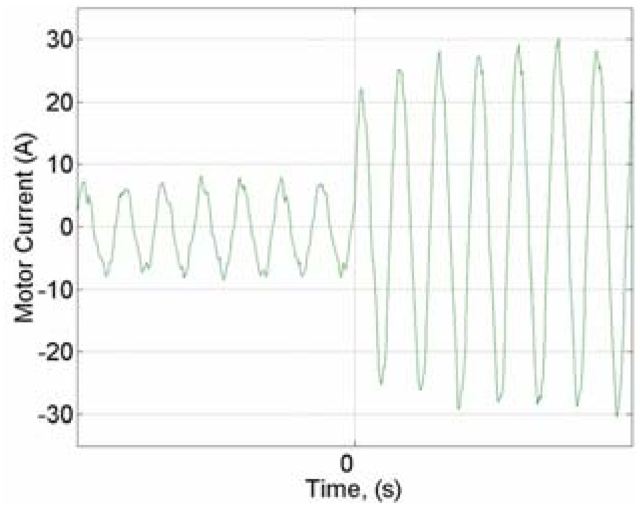
DC currents



D1 motor current



HSS motor current



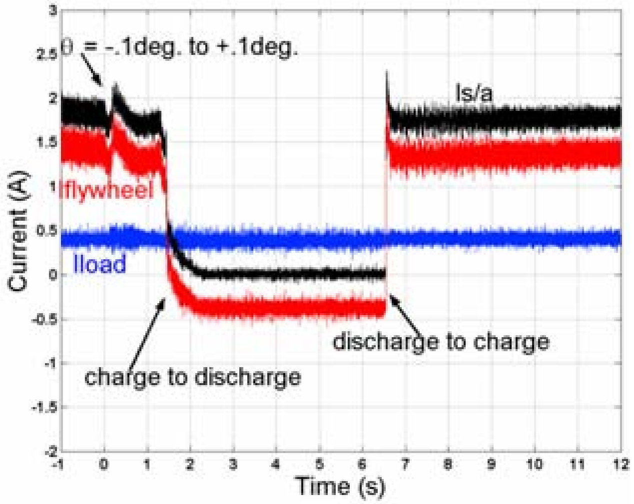
D1 motor current close-up

Initial Closed Position Loop Results

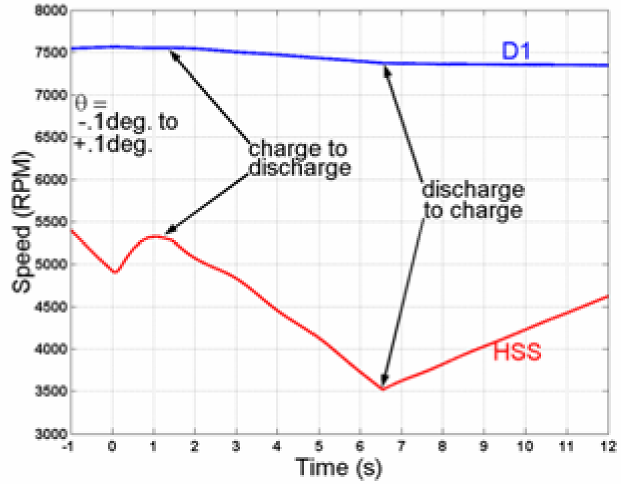
- Closed loop position control-- encoder on air table for position feedback.
- Table torque command provided by PID regulation on table angle (position).
- Control and power cables add a spring constant to the system.

Power Regulation Mode	Commanded Values	Load
Charge $\rightarrow$ Discharge	I^*_{charge} = 1.4 a V^*_{dc} = 120v θ^*_p = -.1° to +.1°	300 Ω

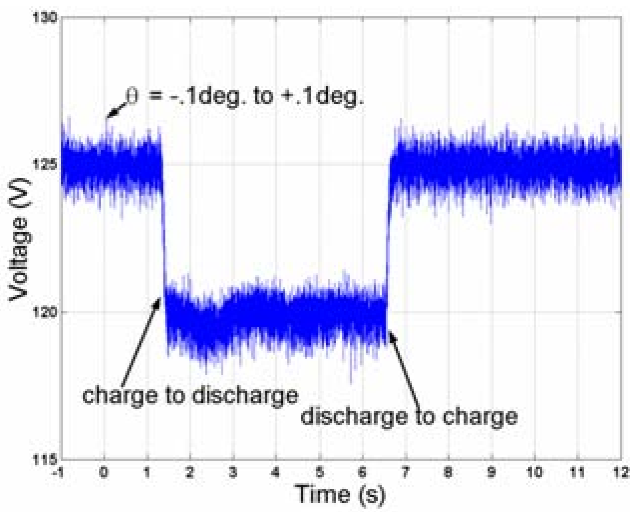
Closed Position Loop Results



DC Currents



Flywheel speeds



DC bus voltage

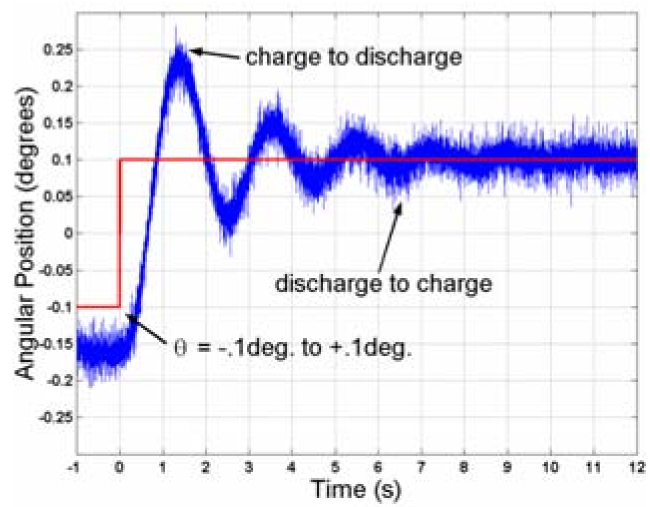
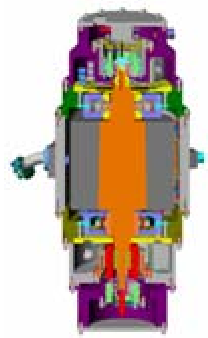


Table position

GRC Future Work

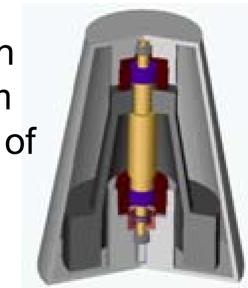
Q1 –
G2 Flywheel
Module Assembly
550 W-hr
1kW
60,000 RPM



Q2-
G2 to
60,000 RPM

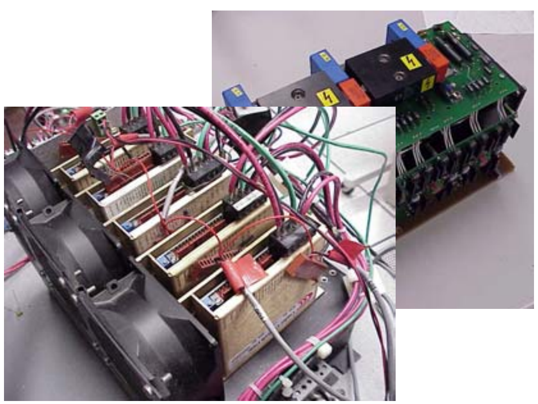
Q4
G3 CDR design
G3-flywheel module which meets the near term performance metrics of the AFTP program

System Metrics:
25 Whr/kg, 85% round trip eff, 15 years LEO



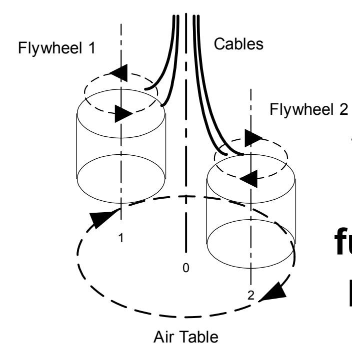
9/2003

9/2004



Q3
M/G & MB electronics upgrade

1) Move to airtable
2) Incorporate lessons learned
3) Build G2 avionics



Q4
Single Axis IPACS With D1&G2

full speed and power levels

Conclusions

- GRC has experimentally demonstrated a single-axis integrated attitude control and energy storage system.

- Simultaneous power bus regulation and attitude control was demonstrated in charge and discharge modes with load, source, and torque command steps.